A NEW WAFER-LEVEL MEMBRANE TRANSFER TECHNIQUE FOR MEMS DEFORMABLE MIRRORS

Eui-Hyeok (EH) Yang and Dean V. Wiberg
Device Research and Applications Section, Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena, CA 91109
Eui-Hyeok.Yang@jpl.nasa.gov

ABSTRACT

This paper describes a new technique for transferring an entire wafer-level silicon membrane from one substrate to another. A 1 μm thick silicon membrane, 100 mm in diameter has been successfully transferred without using adhesives or polymers (i.e. wax, epoxy, or photoresist). Smaller or larger diameters can also be transferred using this technique. The fabricated actuator membrane with an electrode gap of 1.5 μm shows a vertical deflection of 0.37 μm at 55 V. The proposed technique has the following benefits over those previously reported: 1) no post-assembly release process (e.g. using HF) is required and no wax, photoresist, or epoxy is used for the transfer purpose 2) The bonded interface is completely isolated from any acid, etchant and solvent, which ensures a clean and flat membrane surface. 3) offers the capability of transferring wafer-level membranes over deformable actuators.

INTRODUCTION

NASA and its industrial partners are formulating the design of the Next Generation Space Telescope (NGST) which, with an estimated 6-8m diameter aperture and cryogenic operation, will reveal more distant structures of the Universe, but in similar detail at infrared wavelengths. A small, lightweight, cryogenic deformable mirror (DM) has been identified as an enabling technology to achieve NGST science objectives. The MEMS technology is being taken to explore the development of the continuous DM technology with the ultimate application as the active optical surface of space based telescopes.

Micromachined designs have been developed by several research groups to improve the DM technology and offer the potential to be scalable and cost effective. Segmented mirrors [1-3] have been fabricated with individual pixel tip/tilt capability, but a continuous mirror surface is required for astronomical adaptive optics applications. Micromachined continuous membrane DMs have been fabricated by Delft [4] and JPL [5] (the previous JPL design was substantially more rudimentary in approach than that described in this paper). Both have excellent surfaces but the mirror membranes have high inter-actuator coupling between individual pixels (influence function). An electrostatically actuated surface micromachined DM [6] has been demonstrated. This micromachined DM has a continuous mirror backed by parallel plate actuators embodied in the Multi-User MEMS Processes (MUMPS). Restriction to the MUMPS process creates design limitations and marginal surface quality, which in turn limits the applicability of this approach.

A new design for the materials, structures and fabrication methods to meet the requirements of imaging astronomical adaptive optics is necessary. To satisfy this requirement, a novel concept has been taken to develop an electrostatically actuated MEMS-DM with a continuous single crystal silicon (SCS) membrane. In order to realize this concept, a sheet of optical quality single crystal silicon or silicon nitride (with surface area > 1cm^2) should be transferred onto deformable membrane actuators. Batch transfer techniques have been previously demonstrated [7-10]. Some of these techniques are capable of transferring multi-layered structures, but the transfers have succeeded only for localized devices. Wafer level transfer techniques have also been developed, which involved adhesives and/or molding materials [11,12]. However, these techniques are not suitable for multi-layer transfer because adhesives often produce residues over the transferred membrane surface, hindering successive layer transfer. Thus, a new wafer-level transfer technique has been developed for the fabrication of deformable mirrors.

CONTINUOUS MEMBRANE MIRROR DESIGN

Astronomical applications call for optical-quality continuous mirror surfaces. A continuous membrane has the advantage that it does not cause diffraction of the reflected beam, increasing the astronomical sensitivity for imaging and spectroscopic applications. Such membrane also ensures smooth and continuous phase variations across the mirror. Moreover, a device based upon SCS technology will result in a stress free membrane with excellent optical quality. Therefore, a continuous single crystal silicon membrane deformable mirror concept has been proposed as shown in Figure 1 [13]. A continuous SCS mirror membrane constitutes the reflective adaptive surface, which is supported by an array of electrostatic actuators. The actuator is also a deformable membrane attached to the immobile base substrate.

MEMBRANE TRANSFER PROCESS

A 1 μm thick corrugated polysilicon membrane has been transferred onto an electrode wafer to show the feasibility of the proposed technique. The transferred membrane with underlying electrodes constitutes an electrostatic actuator array. An SOI wafer and a silicon wafer are used as the carrier and electrode wafers, respectively. Figure 2 shows the fabrication sequence for multi-layered wafer-level membrane transfer. After thermal oxidation, the Ti/Pt/Au layers are deposited and patterned to form the electrode array on the electrode wafer. The SOI carrier wafer is patterned and etched to define a 5 μm deep corrugation profile. The polysilicon layer is deposited on the carrier wafer (Figure 2 (a)). The Cr/Pt/Au layers are deposited over the photoresist patterns on both wafers for the lift-off process. Since the indium uniformly wets the Au layer, the Au acts as a seed material for hermetic bonding, which is a critical step for the subsequent etch process. The carrier wafer is bonded to the electrode wafer by using evaporated indium as the intermediate material. The EV aligner and thermo-compression bonder have been used. The bond chamber is pumped down to 10E-5 Torr before pressing two wafers. The piston pressure of 4 KPa is applied at 156 °C in a vacuum chamber to provide hermetic sealing (Figure 2 (b,c)). The substrate of the SOI wafer is etched in a 25 wt% TMAH bath at 80

°C until the buried oxide is exposed (Figure 2 (d)). A Teflon fixture is used to protect the backside of the wafer pair as well as their bonded interface. The exposed oxide is then removed by using 49 % HF droplets after an oxygen plasma ashing (Figure 2 (e)). The SOI top silicon layer is etched away by using an SF_6 plasma to define the corrugation profile, followed by the HF droplet etching of the remaining oxide. The oxygen plasma is then used to remove any possible residues on the membrane surface. The wafer-level silicon membrane transfer is completed at this stage (Figure 2 (f)). The SF_6 plasma with a shadow mask selectively etches the polysilicon membrane if the transferred membrane structure needs to be patterned (Figure 2 (g)). The successive single crystal silicon membrane transfers onto a deformable membrane actuator array (Figure 2 (h) is under development.

MEASUREMENTS AND DISCUSSIONS

Electrostatic actuators with various electrode gaps have been fabricated and characterized. Figure 3 shows SEM photographs of a 1 µm thick polysilicon membrane, which has been successfully transferred onto the electrode wafer. The gap between the transferred membrane and electrode substrate is very uniform (+/- 0.1 µm across a wafer diameter of 100 mm, provided by optimizing the bonding control). A WYKO RST Plus optical profiler has been used to measure the static deflection of the membranes. The fabricated actuator membrane with an electrode gap of 1.5 µm shows a vertical deflection of 0.37 µm at 55 V as depicted in Figure 4.

The optical profile measurement results in Figure 5 show that the fabricated actuator membrane is initially deformed upward. The membrane is constrained by the corrugated profile and deflection of a membrane affects the shape of adjacent pixels. A modified actuator design is under development to fabricate actuators array with an uniform membrane profile.

CONCLUSIONS

A new wafer-level silicon membrane transfer technique has been demonstrated by fabricating and testing an electrostatic actuator array. A 1 µm thick silicon membrane, 100 mm in diameter has been successfully transferred without using adhesives or polymers (i.e. wax, epoxy, or photoresist), thus without creating residues and cracks to ensure clean mirror membrane. The complete characterization of successive single crystal silicon membrane transfers onto a deformable membrane actuator array will be performed, and the 4 µm stroke design will also be incorporated to provide the enabling capability for astronomical adaptive optics (e.g. segmented space telescopes). This work paves the way for the development of a more sophisticated critical technology complement for large lightweight space telescopes of the future, whose demanding requirements need the investment in radically new mirror technologies today.

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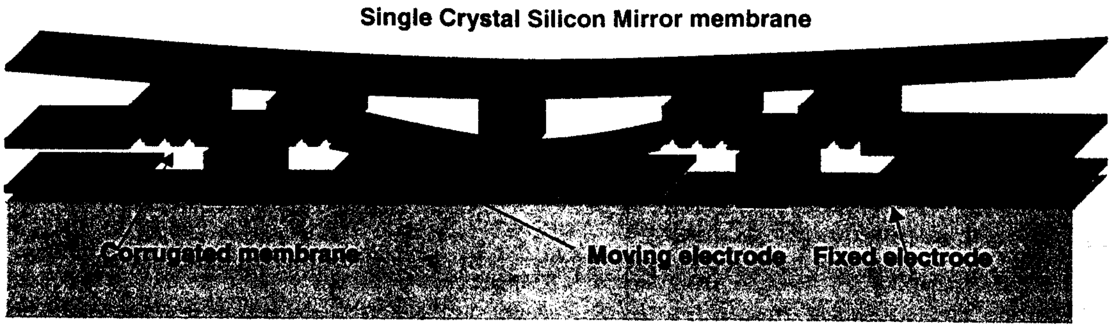


Figure 1 *The concept of the double layered MEMS deformable mirror with a continuous single crystal silicon mirror membrane [1].*

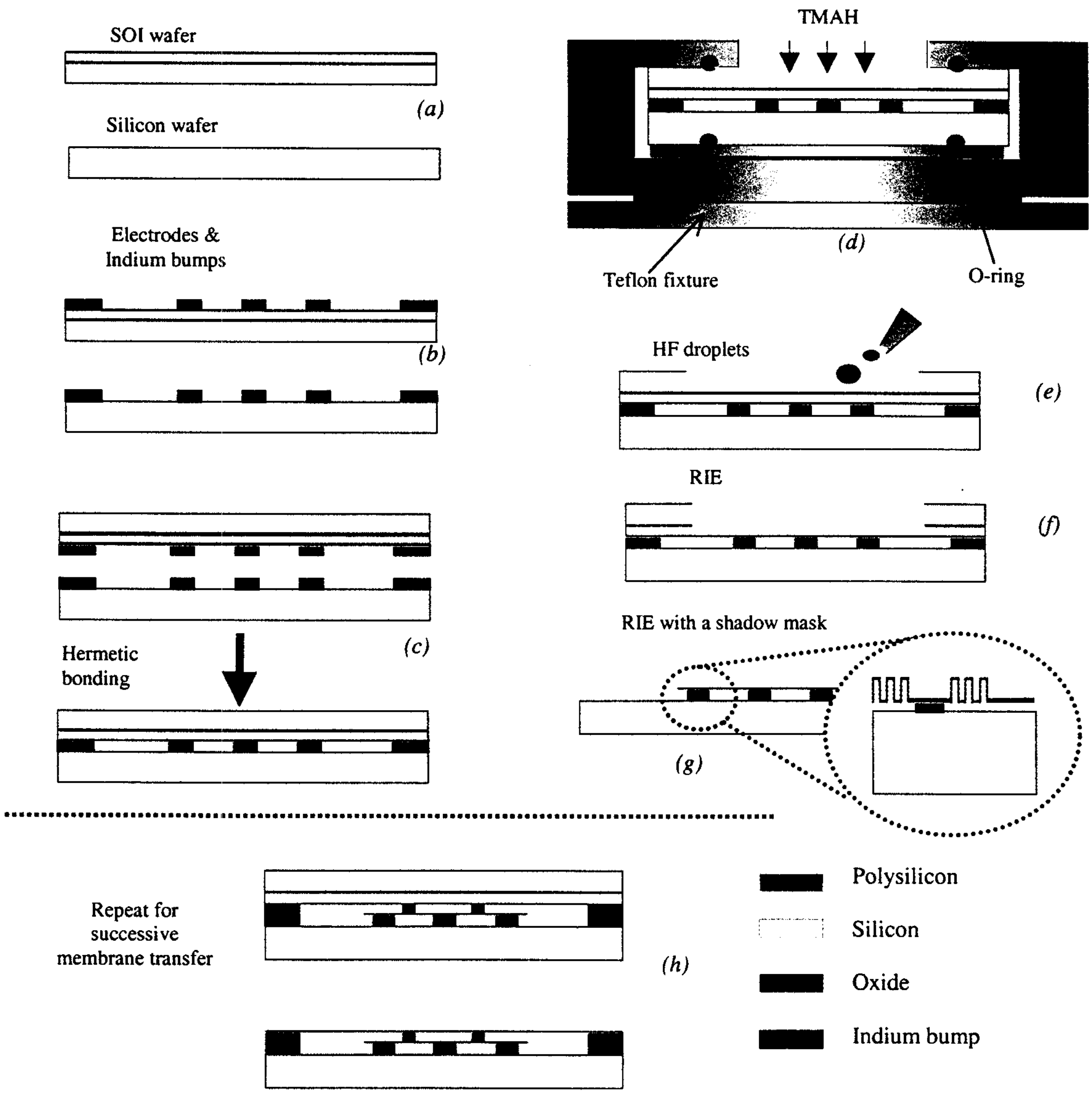
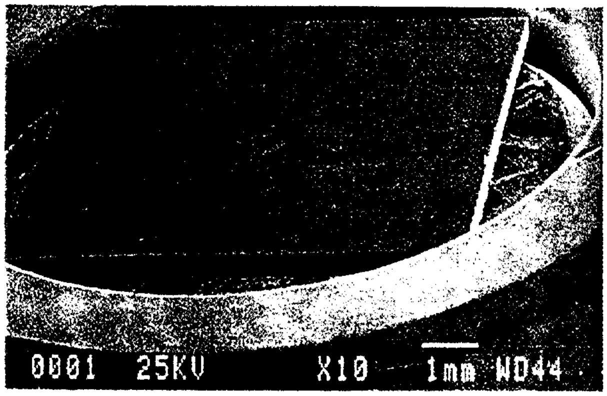
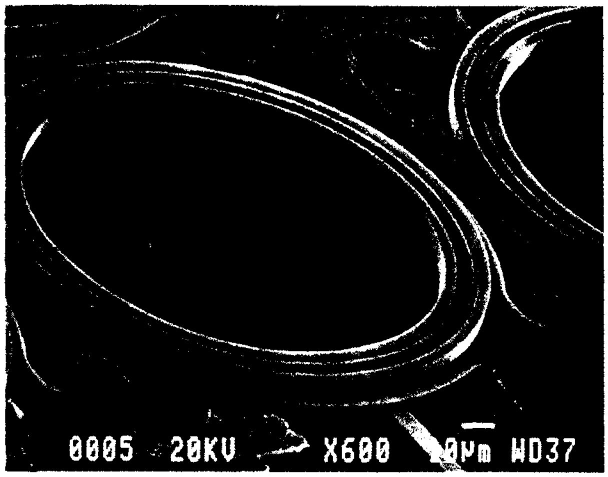


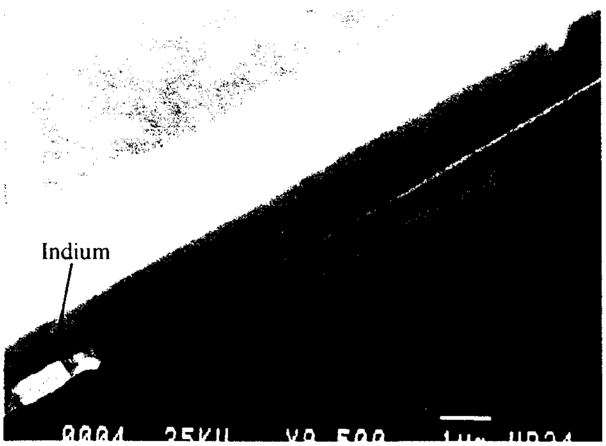
Figure 2 *The membrane transfer process. The successive layer transfer process is identical with the first layer transfer process except for the use of a shadow mask to place Indium bumps over deformable actuators. (a, b) polysilicon deposition, electrode definition & Indium evaporation (c, d, e, f) bonding & etching (g) defining actuator membrane (h) successive layer transfer: a continuous single crystal silicon*



(a)



(b)



(c)

Figure 3 *The SEM photographs of the transferred polysilicon membrane actuator. The transferred membrane (before defining corrugations, diced to 9 mm²) The corrugated deformable actuator. (c) The cross sectional view of an actuator.*

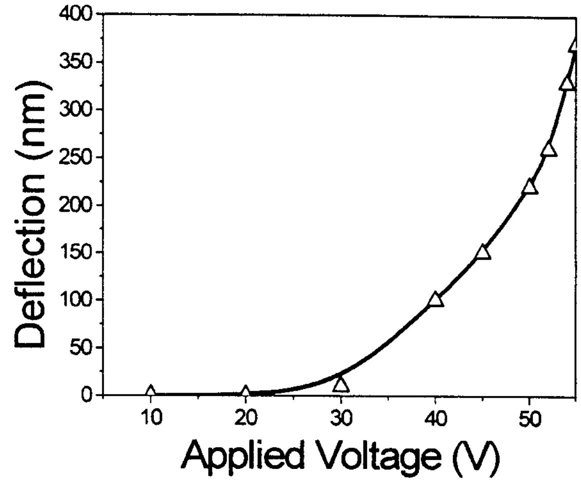
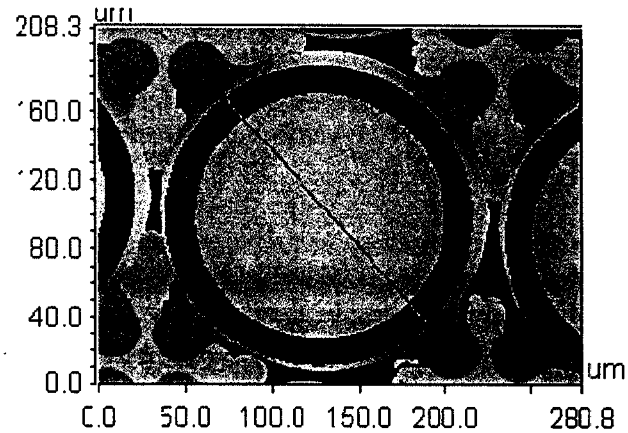
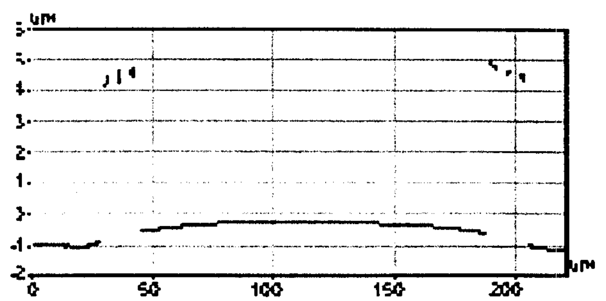


Figure 4 *The deflection characteristic of a transferred membrane actuator.*



(a)



(b)

Figure 5 *Surface profiles of the fabricated actuator array. The center flat membranes show upward deformation by the constraint due to the residual stress in the polysilicon film. This deformation can be reduced by modifying the membrane profile. (a) Surface profile of a actuator membrane (b) 2-D view of the profile of the membrane*